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Vibration Control of the Main Towers of the Akashi Kaikyo Bridge

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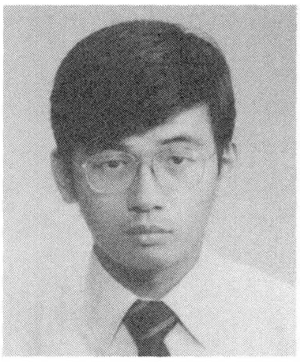

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Summary

The main towers of the Akashi Kaikyo Bridge are 300m tall, and have very flexible feature. The natural frequency of the towers becomes relatively low, and they are easy to vibrate under the wind even after completion of the bridge.
To control the vibration of the towers due to the wind, shape of cross section was improved and Tuned Mass Dampers(TMDs) were installed.
In this paper, the outline of the vibration control of the towers of the Akashi Kaikyo Bridge is reported. Also, the result of vibration tests and field observation is reported.

1. Introduction

The main towers of the Akashi Kaikyo Bridge are 300m tall and 100m taller than the towers of existent suspension bridges. So these towers have very flexible feature and the vibration of the towers due to the wind, not only during construction but after completion of the bridge, is one of the most important issue for the safety of this bridge.
Honshu-Shikoku Bridge Authority (H.S.B.A.) has conducted various investigations, including wind tunnel tests, for many years, and chosen improved cross section and additional damping devices as the control method against wind induced vibration of the main towers of this bridge.
During construction of the tower, measuring instruments were installed on the tower, and vibration tests and field observation were conducted.
In this paper, the design procedure of the vibration control of the towers of the Akashi Kaikyo Bridge is reported. Also, the result of vibration tests and field observation is reported.

2. Outline of the Vibration Control Method

2.1 Outline

To control the wind induced vibration, the cruciform shape of cross section was chosen for the tower shaft and some kinds of mechanical damping devices were installed on the tower.

2.2 Shape of Cross Section

Based on the results of various wind tunnel tests, the cruciform shape of the cross section was selected for the tower shaft. Size of the cut-off at corner varies according to the height of the tower.

With this cross section, the amplitude of out-of-plane vibration becomes lower, and the divergent torsional vibration at high wind velocity is suppressed.

Fig. 1 shows the general plan of the towers.

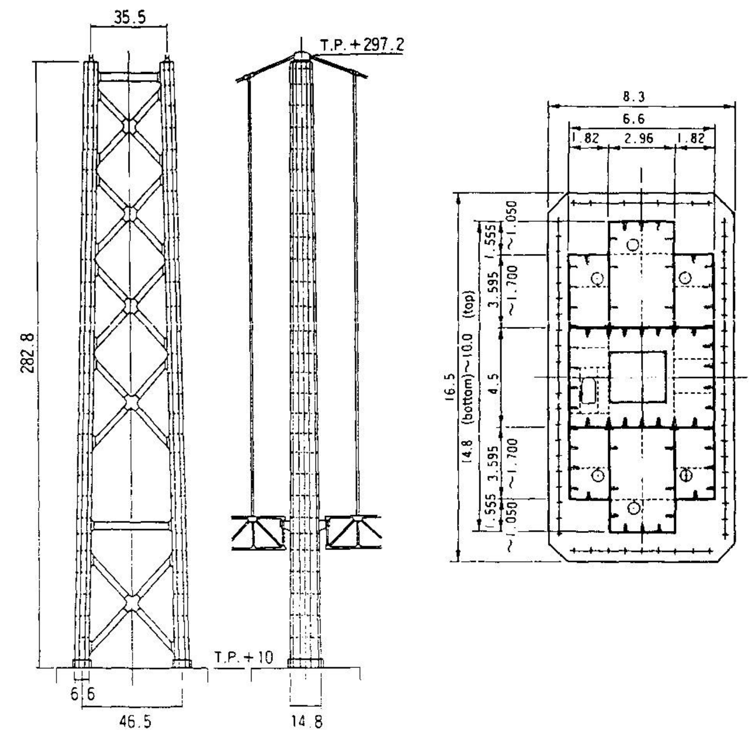


Fig. 1 General Plan of the Towers

2.3 Damping Devices

According to the wind tunnel test with 1/86th large scale model, the amplitude of the vortex induced oscillation by the wind slower than the design wind speed exceeds the allowable amplitude of vibration, and some kinds of mechanical damping devices are needed to reduce the amplitude of vibration.

As the damping device, Tuned Mass Dampers (TMDs), Tuned Liquid Dampers (TLDs), and Friction Dampers, etc. were examined, and Tuned Mass Dampers are chosen from the reliability and cost.

3. Damping Device

3.1 Outline of Design of Damping Device

Wind tunnel tests with 1/86th large scale three dimensional model were conducted for the towers both during construction and after completion of the bridge, and the response of the tower against the wind was obtained.

Based on the results of wind tunnel tests, the resonance wind speed of the vibration and the relationship between the damping of the tower and the amplitude of the vibration were examined. Considering the stress in the member of the tower and the safety of construction work, the condition of vibration control was decided.

3.2 Design Procedure of Damping Device

As the damping device, Tuned Mass Dampers(TMDs) are selected, considering the reliability and cost. During the early stage of construction of the cables, Semi-Active Dampers are installed at the top of the tower.

To design the TMDs, the tower and TMDs are assumed as Two-Degree-of-Freedom (TDOF) System and this system can be treated as the system subject to harmonic loading, because the vibration which should be controlled is vortex-induced oscillation.

Fig.2 shows the procedure to design the TMDs. At first, mass, frequency, and damping of the TMD were assumed. Then, the analysis of TDOF system was conducted and total damping of this TDOF system was obtained. Frequency and damping of TMD were adjusted until total damping of TDOF system satisfied the design damping. This procedure was repeated until minimum weight of TMD was obtained.

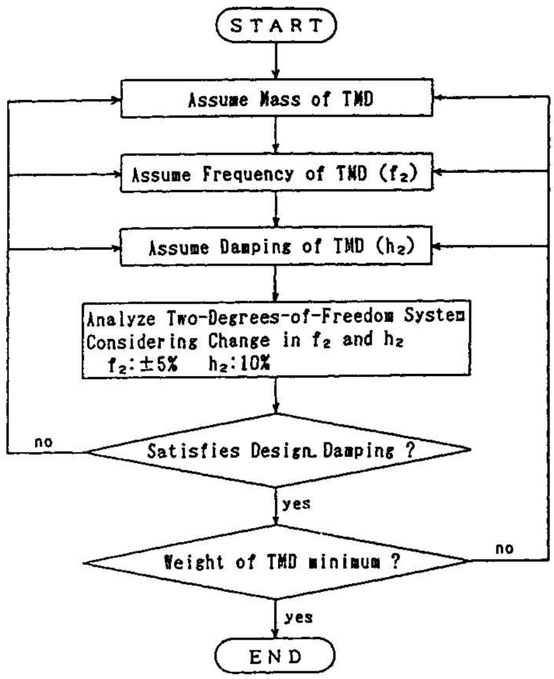


Fig. 2 Design Procedure for TMD

Table.1 shows the TMDs during construction and after completion of the bridge. Fig.3 shows the location of TMDs. The damping devices for each step of construction is as following.

3.3 Damping Devices during Construction of the Towers

During construction of the towers, TMD-E1,E2 against vibration of long period and TMD-E3,E4 against that of short period are installed at the top of the erection crane. Also, TMD-1,2 inside the tower, which are used as the dampers after completion of the bridge, are used as the additional damping.

3.4 Damping Devices during Construction of the Cables and the Girder

During construction of the cables and the girder, TMD-1,2 inside the tower are adjusted to control the vibration. And additional TMDs (TMD-3) are installed at the top of the tower. Also, Semi-Active Dampers are installed at the top of the tower to control the vibration during early stage of construction of the cables.

3.5 Damping Devices after Completion of the Bridge

As the damping device after completion of the bridge, TMD-1 for out-of-plane vibration and TMD-2 for torsional vibration are installed inside the tower.

During Construction of Bridge				After Completion of Bridge		
Frequency (Hz)	Damping Devices	Weight of TMDs		Vibration Mode	Damping Devices	Weight of TMDs
0.6 ~ 1.3	TMD-2 (Inside Tower)	114 ton	→	Torsional (around 0.74 Hz)	TMD-2 (Inside Tower)	114 ton
0.3 ~ 0.6	TMD-1 (Inside Tower) TMD-3 (at the top of Tower)	84 ton 21 ton	→	Out-of-Plane (around 0.44 Hz)	TMD-1 (Inside Tower)	84 ton
~ 0.3	Semi-Active Damper (at the top of Tower)					

Table.1 TMDs during Construction and after Completion of the Bridge

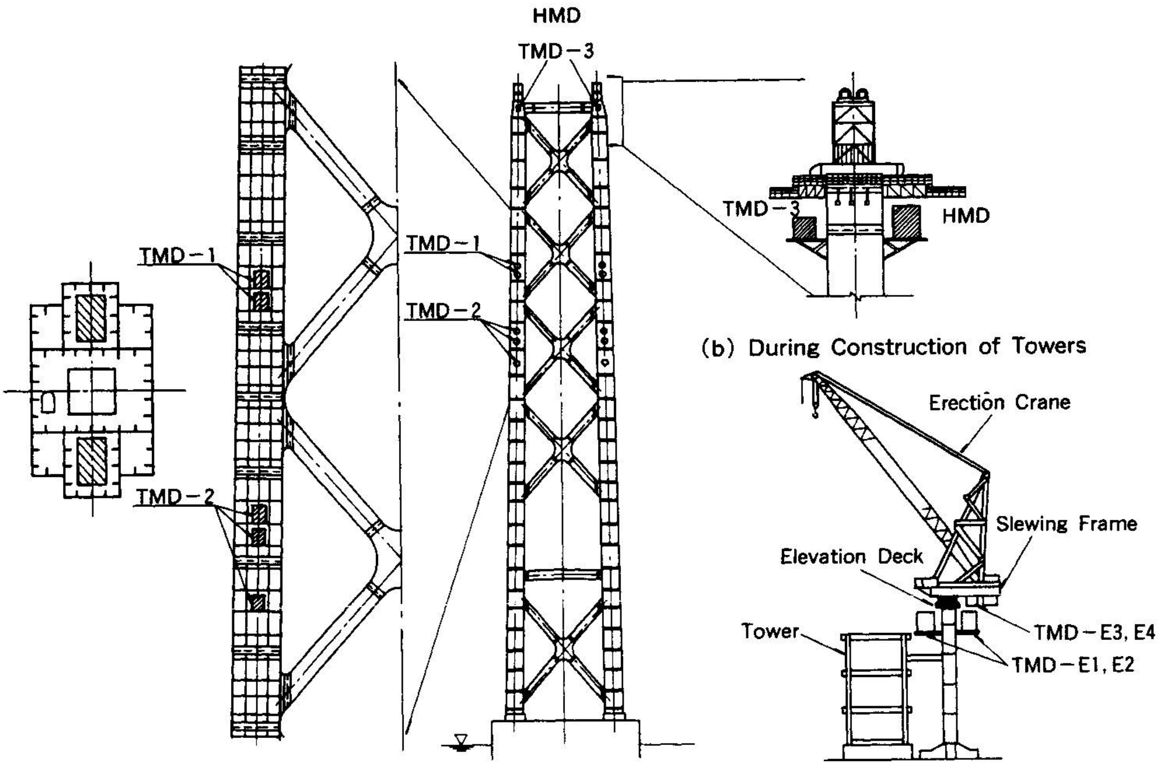


Fig.3 Location of Vibration Control Devices

4. Vibration Test and Field Observation

4.1 Vibration Test

Vibration test was conducted after completion of the tower. The characteristic of the free standing tower without TMDs and the effect of TMDs were examined. The Semi-Active Dampers at the top of the tower were used as oscillators.

Table.2 shows the frequency and mode shape of both measured and calculated values, and they have good agreement.

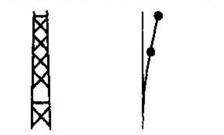
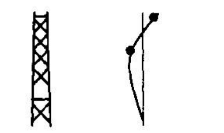
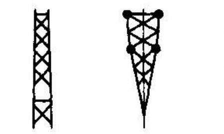
Vibration Mode	Natural Frequency (Hz)		Mode Shape (—— Calculated, ● Measured)
	Calculated	Measured	
Out-of-Plane Vibration 1st Mode	0.127	0.126	
Out-of-Plane Vibration 2nd Mode	0.677	0.673	
Torsional Vibration	0.473	0.471	

Table.2 Natural Frequency and Mode Shape of Free Standing Tower

Table.3 shows the damping (logarithmic decrement) of the tower for each mode of vibration. The damping of the tower for 1st out-of-plane vibration is a little smaller than that specified in design standard, but damping for other mode are bigger.

The additional damping with TMDs satisfies the design requirement for each mode.

Vibration Mode	Test №	AMD	TMD1	TMD2	TMD3	Damping δ		maximum amplitude (cm)
						Measured	Design	
Out-of-Plane Vibration 1st Mode	1	×	×	×	×	0.0067	0.0100	62
	2	P	×	×	×	0.028	0.0244	28
	3	A	×	×	×	0.105	0.0752	19
	4	P	○	○	○	0.038	0.0244	21
	5	A	○	○	○	0.111	0.0752	21
Out-of-Plane Vibration 2nd Mode	6	×	×	×	×	0.038	0.0100	1.3
	7	×	×	○	×	0.080	0.0454	0.9
	8	P	○	○	○	0.096	0.0454	1.0
Torsional Vibration	9	×	×	×	×	0.028	0.0100	5.3
	10	×	○	×	○	0.075	0.0418	3.0
	11	P	○	○	○	0.075	0.0418	3.0

Table.4 Damping (Logarithmic Decrement) of Free Standing Tower

4.2 Field Observation

During construction of the tower, measuring equipment was installed on the tower and the field observation of the behavior of the tower was conducted. The purpose of the field observation is to observe the vibration of the tower and the movement of the TMDs to confirm the design assumption and the effect of vibration control.

Since the measuring instruments were installed on the tower, a lot of records have been collected about the behavior of the tower. For the example of these records, a record about vortex induced oscillation is reported here.

Fig.4 shows the relationship between wind velocity and amplitude of vibration due to the wind of around perpendicular direction. Also the result of the wind tunnel tests are shown in Fig.4.

Considering the record of field observation, it was confirmed that the vibration characteristic of the towers agrees the assumption for the wind tunnel test and effect of the TMDs satisfies the design requirements.

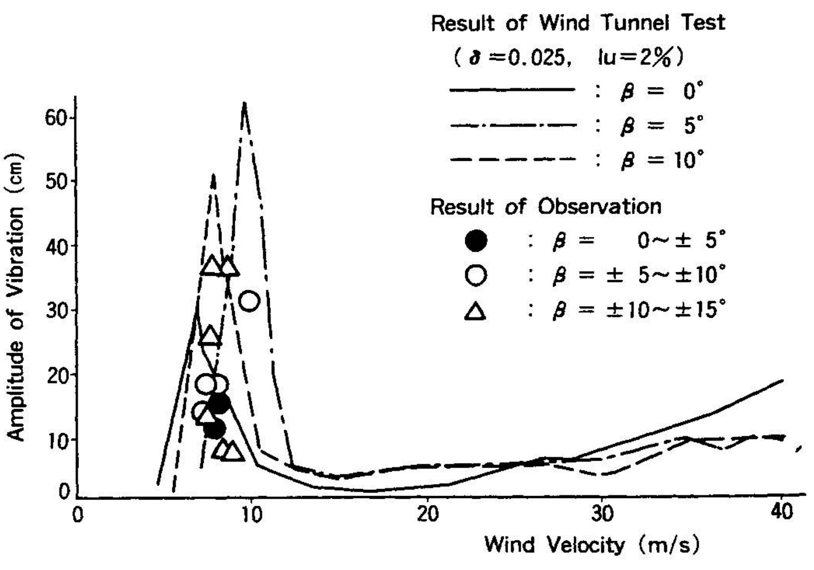


Fig.4 Relationship between Wind Velocity and Amplitude of Vibration

5. Conclusion

In this paper, the design procedure of the vibration control and the result of field observation and vibration tests about the towers of the Akashi Kaikyo Bridge is reported.

Based on the results of various wind tunnel tests, the cruciform shape of the cross section was selected for the tower shaft and Tuned Mass Dampers are installed to reduce the amplitude of vibration..

Vibration tests and field observation were conducted during the construction of the towers, and it was confirmed that the vibration characteristic of the towers agrees the design assumption and effect of the TMDs satisfies the design requirements.

The authors hope that the design conducted for the vibration control of the towers of the Akashi Kaikyo Bridge and result of the vibration test and field observation will contribute the wind resistant design for the same kind of structure in the future.

6. Acknowledgements

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